MEASUREMENT OF BUNCH LENGTH BASED ON BEAM SPECTRUM IN THE KEKB

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Abstract

An amplitude ratio of two frequency components in the beam spectrum gives the bunch length. It is analytically demonstrated that this technique can detect an rms bunch length under that normalized frequencies are less than 1. Such a bunch length monitor was fabricated for the KEKB. Design, hardware and the performance of a bunch-length monitor are described. The bunch length was measured both in single bunch and multi-bunch modes. The average bunch length in multi-bunch mode with a 4-bucket bunch spacing did not indicate a significant difference from that in single bunch mode.

1 INTRODUCTION

The bunch length is an important parameter in electron-positron storage rings. The natural bunch length is generally defined as an rms value of a Gaussian bunch at zero beam current, but it varies as the beam current increases. The bunch length should be measured with high accuracy in order to understand its current dependence. The bunch length can be obtained from the frequency spectrum of a bunch. Monitors of this type have being used in several storage rings [1-5] so far. It is sometimes thought that the monitors are not reliable for measuring bunch shapes that deviate from a Gaussian. But, are the monitors really unreliable for non-Gaussian distribution functions?

2 PRINCIPLE

Suppose that $f(t)$ is a distribution function of a bunch. Its frequency spectrum is given by the Fourier transform

$$F(\omega) \equiv \int_{-\infty}^{+\infty} f(t) e^{-j\omega t} dt. \quad (1)$$

The exponential term can be expanded in series as

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)(1 - j\omega t - \frac{\omega^2}{2} t^2 + j\frac{\omega^3}{6} t^3 + \cdots)dt. \quad (2)$$

Since $f(t)$ represents a bunch distribution, one can limit an integral time region and may set ωt<1 by a proper choice of frequency. Then Eq.(2) can be approximated by the expansion to the second-order term

$$F(\omega) \approx I_0\left[1 - j\omega\bar{t} - \frac{\omega^2}{2}\left\langle t_0^2 \right\rangle\right], \quad (3)$$

where $I_0 = \int_{-\infty}^{+\infty} f(t)dt$, $\bar{t} = \int_{-\infty}^{+\infty} t f(t)dt / I_0$ and $\left\langle t_0^2 \right\rangle = \int_{-\infty}^{+\infty} t^2 f(t)dt / I_0$. The first term of Eq.(3) represents an intensity, the second term is an average position and the third is related to the rms deviation of the bunch, *i.e.* the bunch length. The amplitude of the spectrum is expressed by

$$|F(\omega)| \approx I_0\left\{1 - \frac{1}{2}\left\langle t^2 \right\rangle \omega^2\right\}. \quad (4)$$

Here, $\left\langle t^2 \right\rangle$ is the variance of the bunch distribution. The amplitude of the spectrum drops as ω^2. It is noted that two times of the attenuation coefficient of the beam spectrum is just equal to the variance of the bunch. In order to investigate the frequency dependence, a Gaussian bunch was compared with a parabolic one with the same variance. Though the bunch shapes are different, their amplitudes in the spectra agree to each other within 5%, when the normalized frequency $\omega\sigma_t$ is less than 1, where σ_t is the rms bunch length. Detecting two frequency components $(\omega_2 > \omega_1)$ of the beam spectrum under the condition $\omega\sigma_t < 1$, we have

$$\sigma_t = \sqrt{\frac{2}{\Delta\omega^2} \ln\left\{\frac{F_1(\omega_1)}{F_2(\omega_2)}\right\}}, \quad (5)$$

where $\Delta\omega^2 = \omega_2^2 - \omega_1^2$. This is the same equation as that derived for a Gaussian distribution. Therefore, we can obtain the rms bunch length by measuring the attenuation coefficient in the spectrum.

3 RMS BUNCH LENGTH MONITOR

KEKB [6] is an asymmetric electron-positron collider with two storage rings, named LER and HER. Approximately 5000 bunches are designed to be stored with a 2 ns bunch spacing in each ring, where the harmonic number is 5120. Basic parameters are listed in Table 1. In order to raise the luminosity, the vertical beam size at the collision point is squeezed by reducing the betatron function to less than 1.0 cm. Thus a short bunch length is desirable. In order to make the bunch length short, a small momentum compaction, on the order of 10^{-4}, is allowed by design.

Since the bunch length is expected to be less than 10 mm, the pick-up electrode is required to have good sensitivity in the giga-hertz region. If bunches are stored in every bucket, beam spectrum components exist only at harmonics of the rf acceleration frequency. Thus the lower detector frequency, ω_1, was chosen to be around the fundamental frequency of 509 MHz. The bunch length is given from Eq.(5) by

$$\sigma_L{}^{(mm)} = \frac{204.9}{\sqrt{n^2 - 1}} \sqrt{\log\left(\kappa \frac{V_1}{V_2}\right)}, \quad (6)$$

where n is the harmonic number of the rf frequency, κ is a compensation coefficient for detector gain and V_1, V_2

are voltages detected at the lower and higher frequency, respectively. Higher frequency detection evidently has less measurement error. However, mixing of wake fields should also be considered. In order to avoid wake fields effects, the cut-off frequency of the vacuum chamber with the pick-up electrode should be raised by reducing its diameter. However, the aperture of a chamber needs to be determined from a point of view of beam dynamics. A chamber with a diameter of 64 mm is used; its cut-off frequency is 2.7 GHz. Thus the upper detected frequency is chosen to be 2.5 GHz. Since the detection frequency is low, a high resolution detector is required. Assuming that the detector has an error of 1% for detecting bunch length of 5 mm, the error in the measured bunch length is expected to be 0.7 mm.

Table 1 : Parameters of KEKB used in this measurement.

Parameter	HER	LER
Beam Energy, E (Gev)	8.0	3.5
RF Frequency, f_{rf} (MHz)	508.886	
Revolution Frequency, f_0 (kHz)	99.39	
Harmonic Number, h	5120	
RF Cavity Voltage, V_c (MV)	9.0	5.0
Synchrotron Frequency, f_s (kHz)	1.17 - 1.68	1.14 - 1.85
Momentum Compaction, $\alpha \times 10^{-4}$	1.88 - 3.39	1.41 - 3.13
Momentum Spread, $\delta_\varepsilon \times 10^{-4}$	6.67	7.31
Energy loss/turn, U_0 (MeV)	3.49	0.85

A block diagram for a detector is shown in Fig. 1. A beam pulse from a button electrode in the LER or in the HER is split into two channels to extract two frequency components using band-pass filters. The band-pass filters have the same bandwidth of 50 MHz. Two signals passing through the band-pass filters are mixed down to the same frequency of 70 MHz by local oscillators which are commercially available signal generators. Each 70 MHz signal is detected using two synchronous detectors. The frequency response of the synchronous detectors is 1kHz which is almost equal to the synchrotron frequency. Two detected voltages V_1 and V_2 are put into an analog calculator unit (ACU). The ACU produces a signal proportional to the bunch length. An output signal of the ACU is read by a digital multi-meter.

The gain between the two channels should be adjusted to compensate for the frequency response of the transfer function from the pick-up electrode through the detector. The ATT-2 and ATT-3 shown in Fig.1 are prepared for adjusting the gain. The ATT-2 can control the gain of channl 1 with a step of 0.25 dB or 2.9%. Since the gain control is large, the ATT-3 can adjust the gain of channel 2 more precisely by changing the length of a thin and lossy cable (RG174/u). The characteristics of the detector was investigated using a cw source instead of a pulse signal. The linearity of both channels extended over 30 dB, where the maximum level was -50 dBm. The voltage ratio is accurate to within $\pm 2\%$ including measurement error, which means that an error in bunch length is expected to be less than ± 1 mm when the bunch length is 6 mm.

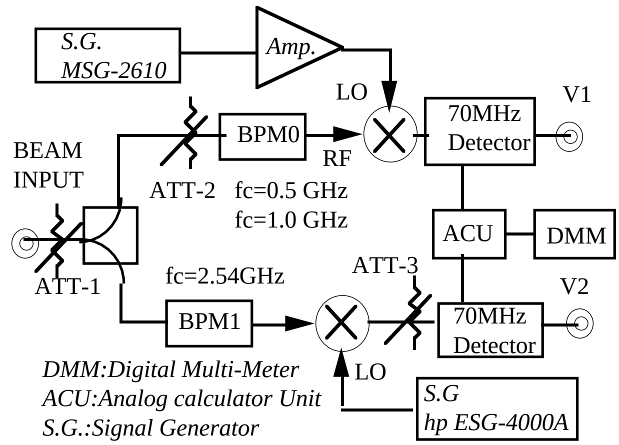

Figure 1: Schematic block diagram of rms bunch length monitor. V1 is voltage of channel 1 and V2 for channel 2.

4 MEASUREMENT

The fundamental component of the rf frequency was used for one of detected frequencies at the beginning. But, noise from the rf power system severely handicapped detection of the signal. Thus detected frequencies were changed to spectrum sidebands, because the spectrum equally appears in every harmonic in single bunch operation mode. The measurement was performed using the side-band spectra, $(h-8)f_0$ and $(5h-8)f_0$ when in single bunch mode [7]. However, detecting side-band frequencies during multi-bunch operation gave unreasonable results. The monitor indicated abnormal bunch lengthening or shortening as the beam current increased. Moreover, the monitor depended on the intensity balance between the bunches. Due to these difficulties, we changed the detection frequency to a harmonic of the rf frequency, $2f_{rf}$ instead of f_{rf}.

The monitor was tested using various filling patterns in multi-bunch mode, detecting the frequencies, $2f_{rf}$ and $5f_{rf}$. The number of stored bunches was varied from 33 to 1152 in the LER to investigate the effect of changing the filling patterns. Note that a 4-bucket spacing was used for all filling patterns. We find in Fig. 2 that the results are almost independent of filling pattern, assuming that all bunches in a filling pattern have the same intensity. The monitor showed a good stability of less than 0.1 mm in the bunch length measured over the short term. A significant change was not observed when going from collision to non-collision. The bunch length was also measured during an injection mode. The results are shown in Figs. 3 and 4. It is noted that the momentum compaction differs from that measured in single bunch mode [7], thus the natural bunch length differs from that in single bunch mode. We have found that the bunch length in the HER increases by about 0.5mm as the bunch current increases up to 0.4 mA when the number of bunches is 870. The bunch lengthening can be predicted from that obtained in single bunch mode. On the other hand, the bunch length in the LER increases by about 0.3 mm when the bunch current increases from 0.4 mA to 0.5 mA as shown in Figs. 2 and 4. This bunch lengthening is consistent with that in single bunch mode in the LER.

When the beam current reached 500 mA with 870 bunches in the LER, it was observed that the bunch length rapidly increased from 7 mm to 8 mm, and also synchrotron oscillations were excited. This abnormal bunch lengthening would not be real, because the beam spectrum is modified by the synchrotron oscillation. The maximum amplitude of the oscillation was about ±25ps. The longitudinal instability was surpressed by re-adjusting the position of the collimator and the abnormal bunch lengthening disappeared at the same time. This collimator is also considered to be a significant transverse impedance source [8].

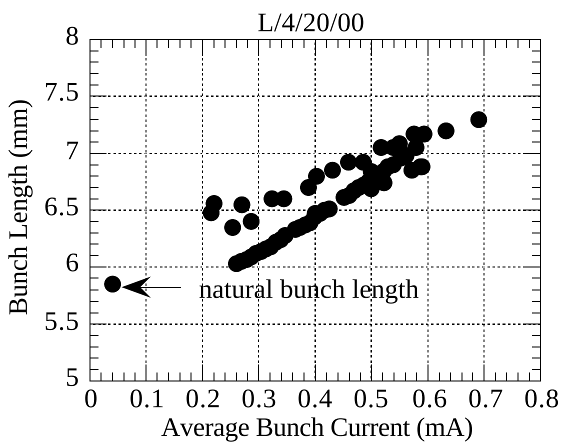

Figure 2: Average bunch length *vs*. average bunch current in six kinds of filling patterns. The number of stored bunches varies from 33 to 1152 with a 4-bucket spacing in the LER. The average bunch current is a value of total beam current divided by the number of bunches in each pattern.

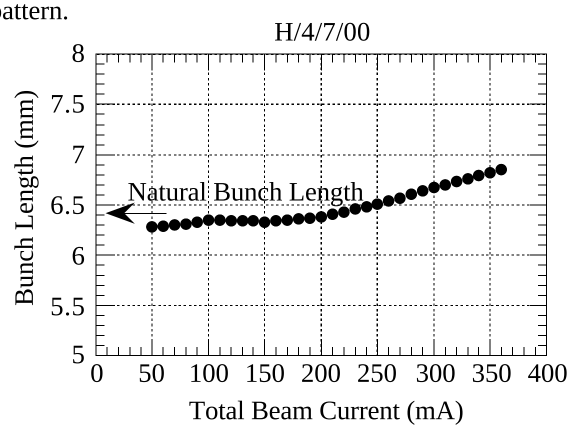

Figure 3: Average bunch-length *vs*. total beam current in the HER, when the number of bunches is 870. The natural bunch length is 6.4 mm.

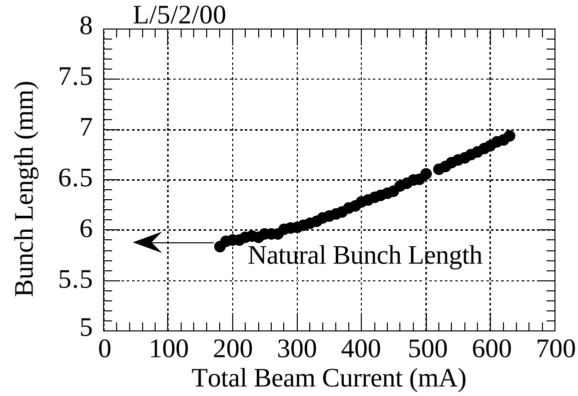

Figure 4: Average bunch-length *vs*. total beam current in the LER, where the number of bunches is 1152. The total current of 600 mA corresponds to a bunch current of 0.52 mA. The natural bunch length is 5.8 mm with $\alpha = 3.1 \times 10^{-4}$.

In conclusion, the rms bunch length can be measured using the low frequency part of the beam spectrum. The measured bunch lengths in both rings show that the averaged bunch length in multi-bunch mode, with a 4-bucket spacing, roughly agrees with that in single bunch mode. Further study is needed with different multi-bunch configurations. The author would like to thank Dr. K. Bane for carefull reading of the manuscript.

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